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Development and application of RF techniques for formation of preionized plasma in the target chamber

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Abstract

Recent heavy ion fusion reactor concepts require multiple beam focusing beyond the space-charge limit. Propagating the beams in dilute plasma potentially can achieve charge neutralization. Here, we apply well known plasma waves to the formation of large-volume uniform plasmas to achieve the required plasmas for charge neutralization. A number of plasma waves will be considered including whistlers, electron cyclotron, and helicon waves. The goal is to produce a large-volume plasma design that will be tested and integrated into near-term ion beam focusing experiments. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently, heavy ion fusion research has developed a reactor design, referred to as HIBALL-II [1]. Multiple heavy ion beams must be focused together in the target chamber at the emittance limit. Near-term experiments, the planned High Current Experiment (HCX) [2], and the Integrated Research Experiment (IRE) will investigate the most promising neutralization methods. One approach utilizes multiple heavy ion beams, charge neutralized by large-volume plasma. The charge neutralization was modeled as a heavy ion beam propagating through a highly ionized cylindrical plasma column [3]. The cold plasma ions motion is neglected, and electrons from the plasma cylinder move into the beam channel, reducing the net positive beam charge over the larger volume of the plasma channel. Ion beam densities will be in the range of 10^{10}–$10^{11}\,cm^{-3}$. Present calculations require the plasma to exceed 1 m in length with an electron density comparable to 1–100 times the beam density. In this paper, we describe a number of plasma sources capable of producing large-volume plasmas to support neutralization studies. It is anticipated to produce RF plasma in the drift section between the last magnetic lens and the reactor chamber. The sources have been well characterized and applied to plasma processing of semiconductor devices.

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2. Background

Plasmas of large dimension are not readily uniform. Plasmas made with electrodes are naturally heterogeneous in the vicinity of the electrodes. Alternatively, electromagnetic waves can be employed. Electromagnetic waves used to produce unmagnetized plasmas at pressures expected in the target chamber are collisionally damped. Consequently, unmagnetized plasmas made with electromagnetic waves are naturally heterogeneous because the skin depth determines the plasma scale length. The skin depth, d, is

$$d = (2\nu/\omega)^{0.5} c/\omega_{\mathrm{pe}} \quad (1)$$

where ν is the collision frequency, ω is the wave frequency, and ω_{pe} is the electron plasma frequency. For radio frequency waves and microwaves, the skin depth is on the order of 1 cm and 1 mm, respectively. Consequently, it is difficult to make large-volume unmagnetized plasmas with electromagnetic waves. Increasing the power to these plasmas does not increase the plasma volume.

3. Wave damping and plasma sources, collisional damping

In the event the target chamber pressure remains high after target ignition (200–1000 mTorr), wave damping will be dominated by collisions. At pressures in the range of 100–1000 mTorr, the plasmas that have been typically formed are not fully ionized. Fortunately, the problem of increasing electromagnetic wave penetration in partially ionized collisional plasmas has been theoretically studied [4]. The studies have identified the whistler wave as favorable for the creation of large-volume plasmas for semiconductor processing. The whistler wave propagates along magnetic field lines ($k \| B$), and was first discovered propagating in the Earth's magnetosphere. The approximate dispersion relation for whistler waves is

$$N^2 = [1 + \omega/(\Omega_{\mathrm{ce}}\omega(1 - \omega/\Omega_{\mathrm{ce}})] \times F(\nu/(\omega - \Omega_{\mathrm{ce}})) \quad (2)$$

where N is the index of refraction, $F(x) = (1 - jX)/(1 + X^2)$, and $\omega < \nu, \Omega_{\mathrm{ce}}$. The propagation characteristics and wave damping can be examined from the real and imaginary components of the index of refraction. Fig. 1 shows a plot of the real part of the index of refraction as a function of electron density. The index is continuous and is always greater than zero, indicating that there are no resonances or cutoffs to limit wave accessibility at any density. This is a unique characteristic that allows access to all density ranges with one heating frequency.

From the imaginary part of the index, the scale length of the absorption can be calculated. In the range of 100–1000 mTorr, the collisional damping of the wave is significant and contributes to the short skin depth of the plasma. However, with the addition of a modest magnetic field (e.g. 10 s G), the absorption scale length can be increased to meters in length at densities near $10^{10}\,\mathrm{cm}^{-3}$. Control of the skin depth of plasmas is directly observed in the electron absorption power density, P_{abs}, including collisionality and magnetic field:

$$P_{\mathrm{abs}} = \frac{e^2E^2}{4m\nu}(\nu^2/((\omega - \Omega_{\mathrm{ce}})^2 + \nu^2) + \nu^2/((\omega + \Omega_{\mathrm{ce}})^2 + \nu^2)) \quad (3)$$

where e is the electron charge, E is the wave electric field, m is the electron mass, and Ω_{ce} is the electron cyclotron frequency. For the whistler wave, $\omega \ll \nu, \Omega_{\mathrm{ce}}$, and therefore the absorbed power density can be reduced by increasing the

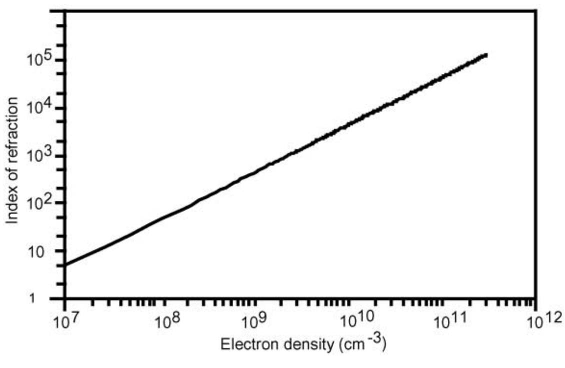

Fig. 1. Real part of the index of refraction for the whistler wave as a function of electron density.

cyclotron frequency until it is comparable to the collision frequency ($v \sim \Omega_{ce}$). The absorption for 13 MHz waves at 100 mTorr can be affected by introducing 30 G of axial magnetic field (Fig. 2). The electron density is selected to be comparable to the beam density ($\sim 10^{10}\,cm^{-3}$). This level of axial magnetic field will not adversely affect beam focusing. By changing the magnetic field, the plasma length can be adjusted to achieve beam neutralization. The same technique has been used to make large-volume plasmas for the manufacturing of semiconductor chips. The qualitative effects of a modest magnetic field at high collisionality have been tested in a small linear machine at the Princeton Plasma Physics Laboratory. 40 MHz waves are launched parallel to the magnetic field in a linear device. The pressure was near 500 mTorr in argon gas. With no magnetic field, a plasma is formed near the window with axial dimensions consistent with the RF skin depth (~ 1 cm). An axial magnetic field of 25 G was added. The plasma then extended in length to about 30 cm, the length of the magnet set. By rapidly turning on and off the magnetic field, the length of the plasma could be instantly changed. These results are in qualitative agreement with the theory outlined above. By operating at lower frequency and lower electron density, the plasma length can be greatly extended. Similar results were obtained by Mantei [5] in plasma produced with microwaves.

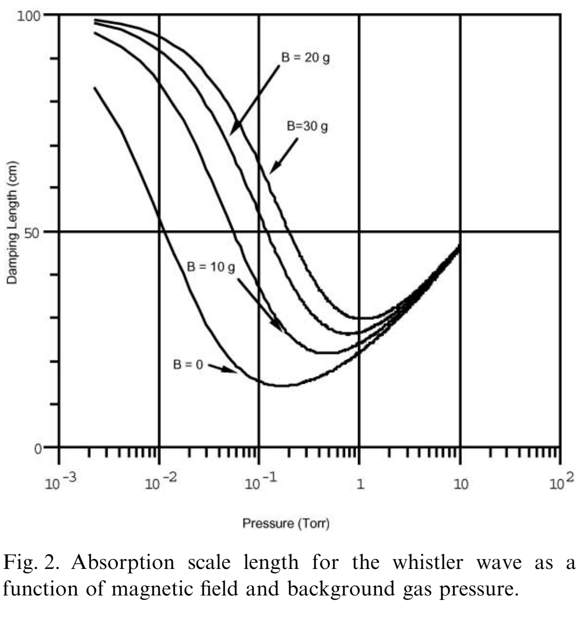

Fig. 2. Absorption scale length for the whistler wave as a function of magnetic field and background gas pressure.

3.1. Collisionless damping

If the target chamber pressure is in the range of 1–100 mTorr, Helicon waves [6,7] and electron cyclotron resonance (ECR) waves are applicable. Both waves require a magnetic field to achieve damping. Helicon sources have recently been developed into a process plasma source for etching. The antenna is either a helical strap or a set of cylindrical straps around a cylindrical dielectric ($k_\parallel$ defined by the antenna). Damping mechanisms are collisional and Landau damping. The helicon dispersion relation strongly couples the axial magnetic field, the density and the wave frequency according to

$$\frac{\omega}{k} = \frac{A}{(ae\mu)}\left(\frac{B_z}{n_e}\right). \quad (4)$$

Helicons have typically operated at densities of 10^{12}–$10^{14}\,cm^{-3}$. Another complexity of utilizing Helicon waves is the species of the operating gas. There are many examples of Helicon waves making argon, xenon, and nitrogen plasmas, but little indication of operation with hydrogen and helium. If low-charge-state gases are required to effectively charge neutralize heavy ion beams, some development of the Helicon source will be necessary. The sources typically operate at field of 100–300 G.

For ECR, the wave will be launched parallel to a magnetic field, similar to the whistler wave. Wave damping depends upon the plasma temperature, density, collisionality and the proximity of the wave frequency to the cyclotron frequency. The damping can be either collisional, Landau or cyclotron damping ($\omega \sim \Omega_{ce}$), and has the following characteristics:

Collisional damping:

$$k_{\parallel i} = k_\parallel \{[(1 + v_c^2/\omega^2/(\beta - 1)^2)^{1/2} - 1]/ [(1 + v_c^2/\omega^2/(\beta - 1)^2)^{1/2} + 1]\}^{1/2}. \quad (5)$$

Landau damping:

$$k_{\parallel i} = 2(\pi)^{1/2}k_{\parallel}/[(\beta - 1)(1 + k_{\parallel}^2/k^2)]\zeta_0^3 \exp\{-\zeta_0^2\}$$

$$\zeta_0 = \omega/(k_{\parallel} v_{th}). \tag{6}$$

Cyclotron damping:

$$k_{\parallel i} = (\pi)^{1/2}\omega_{pe}^2/(2c^2k_{\parallel}^2)]\zeta_0 \exp\{-\zeta_1^2\}$$

$$\zeta_1 = (\omega - \omega_{ce})/(k_{\parallel} v_{th}). \tag{7}$$

The ECR wave will require a magnetic field, but it can be modest (~ 10 G) if the source frequency is at 13 MHz. Similar plasmas have been produced using whistler waves by Stevens [8].

4. Integration into a reactor and near-term experiments

One can integrate plasma into the reactor configuration by streaming it into the ion beam drift tubes between the last focusing quadrupole and the target chamber. The plasma can stream out of a compact source and into the drift tubes. There is adequate space for the plasma source to be integrated with the drift tube. Plasma densities on the order of 10^{13}–10^{14} cm^{-3} can easily be created. This configuration does not necessarily require a magnetic field in the beam drift tubes. If a magnetic field is required, a small field of 30 G is sufficient to assure that the plasma is not cooled by the drift tube wall. With the pressure in the drift tube below 100 mTorr, an ECR or Helicon source can be employed. A magnetic field is required with these two sources. For higher pressures, a collisional whistler wave source is better suited, and a magnetic field (~ 30 G) will be required in the drift tubes. For these sources, plasma can potentially stream 1–3 m down the drift tubes, and at densities 1–100 times the heavy ion beam density. If the base pressure in the drift tube is mainly from the vapor pressure of Flibe in the reactor chamber, then the plasma source should either be an ECR or collisional whistler source because they can form plasma from any vapor or gas.

A full-scale reactor will not be built for some time. However, there are present and near-term scaled-parameter experiments to examine the underlying physics of heavy ion inertial fusion, which offer the opportunity to develop beam charge neutralization techniques [9]. In near-term experiments, it is important to study charge neutralization in ion beams with substantial space-charge potential. The high space-charge potential disrupts the ion beam focusing. Presently, there is a Scaled Final Focus Experiment [10] at Lawrence Berkeley National Laboratory to investigate the ballistic focusing of a heavy ion beam using a series of magnetic quadrupoles. The HIBALL II reactor design incorporates 10 GeV Bi^+ beams and has been experimentally reproduced with 160 keV Cs^+ ions at one-tenth scale. The ion beam density is 10^7 cm^{-3} and the background pressure is 10^{-7} Torr. The high pressure in HIBALL-II is a result of the expected debris in the target chamber. The low (~ 5 V) space-charge potential in the Scaled Final Focus Experiment makes it a non-ideal experiment for studying charge neutralization. Alternatively, the next-step High Current Transport Experiment is presently being designed [2]. It will explore non-scalable transport issues at driver-scale line-charge density, and verify machine aperture clearances. This experiment will begin in 2001. The ion beam energy and density are in the range of 1.6–2.0 MeV and 10^8 cm^{-3}, respectively. Both Helicon and ECR sources will be considered because the drift tube pressure is less than 1 mTorr in both the Scaled Final Focus Experiment and the High Current Transport Experiment. Other facilities will also be considered. Results from near-term experiments will provide confidence in next-generation Integrated Research Experiments, leading to a full-scale driver for energy production.

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